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Now that the limits of GaAs are being reached, the emerging technology of indium phosphide (InP) and its related alloys, such as InGaAs and InAlAs, are further extending the limits of solid-state capabilities in a range of areas from extra-high frequency (EHF) power and photonics to energy conversion applications to a host of military systems.

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Indium phosphide speeds past GaAs

BY LOUIS J. MESSICK
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In the past couple of decades, maturing GaAs-based semiconductor technology has complemented silicon technology both by extending transistor frequencies into the millimeter-wave region and by making new optoelectronic devices and circuits possible. However, now that the limits of GaAs are being reached, the emerging technology of indium phosphide (InP) and its related alloys, such as InGaAs and InAlAs, are further extending the limits of solid-state capabilities in a range of areas from extra-high frequency (EHF) power and photonics to energy conversion applicable to a host of military systems.

> **Emerging InP technology and related alloys like InGaAs and InAlAs are extending the limits of solid-state capabilities.**

Although it's been expected for some time that InP-based devices would outperform current materials, their development requires time and money, just as did the development of the Si and GaAs technologies. For each material, the basic skills and capabilities must be developed.

The first capability needed is the growth of bulk material. Ten years ago, the maximum single crystalline InP ingot diameter was approximately 1 cm; today, however, 3-inch ingots are routinely grown. In addition, the material quality is improving significantly. For example, Sumitomo, using the "Liquid Encapsulated Czochalski" (LEC) method under phosphorous pressure (VCZ method), has grown low-dislocation-density 50-mm-diameter Sn-doped InP crystals with average etch pit densities of 2 × 10^3 cm^{-2}. This is an order of magnitude lower than that of conventional LEC crystals with the same doping density.

Similar dislocation densities have also been achieved with Fe-doped semi-insulating InP, which can serve as substrate material for a variety of millimeter-wave devices. Within the United States, Crystacomm Inc. (Mountain View, Calif.) is both improving material quality and supplying InP substrate material to the various R&D facilities.

The fabrication of state-of-the-art high-speed electronic and optical devices requires not only high-quality substrate material, but the growth upon these substrates of highly uniform epitaxial layers with precisely controlled physical and electronic parameters such as thickness, carrier concentration, carrier mobility and layer smoothness. In some applications, only a single layer may be required while in others, extremely complicated structures containing thousands of layers are necessary.

Rapidly maturing epigrowth techniques, such as organo-metallic chemical vapor deposition (OMCVD) and gas-source molecular beam epitaxy (GSMBE), are now making possible the InP-based structures that are needed for the advanced devices awaited by the military community.

InP is an attractive material for microwave and millimeter-wave power transistors because of its higher-peak electron drift velocity, thermal conductivity and breakdown field as compared to GaAs. In addition, the surface properties of InP make using the metal-insulator-semiconductor field-effect transistor (MISFET) possible, and this allows both channel carrier accumulation and large positive gate voltage swings while keeping gate leakage current extremely small.

InP MISFETs developed by the Naval Ocean Systems Center (NOSC) and by Thompson-CSF have demonstrated power outputs of 4.5 W/mm of gate width at 46 percent power-added efficiency at X-band. This is more than three times the power per unit gate width ever reported for GaAs-based FETs.

More recently, a collaborative effort between Texas Instruments and NOSC has resulted in ¼-micron gate-length InP MISFETs demonstrating 1.8 W/mm at 30 GHz while the highest reported value for GaAs-based FETs is 1 W/mm at that frequency. Under dc conditions, these devices exhibit drain current drift due to charging or discharging of states at or near the semiconductor/gate-insulator interface; however, when used as microwave amplifiers their drift is extremely slight.

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CAD VOYAGES THROUGH 'VIRTUAL REALITY'

CyberSpace travel

BY RICHARD DOHERTY

Sausalito, Calif. — Scientists at NASA's Ames Research Center, working with CAD houses like AutoDesk Inc., may soon take users of computer-aided design tools where no engineers have gone before—journeying over, under, around and through CyberSpace, a computer-generated "virtual reality."

And with NASA's View (Virtual Environment Interface Workstation), these CyberSpace explorers will never have to leave their armchairs. Instead, they'll don stereoscopic goggles and a "smart glove" (both tied to a host computer via sensors) to explore a world of wire-frame and fully shaded images, traveling over vast distances in the blink of an eye (see sidebar).

The goggles ensure that the viewer's entire field of vision is filled with images displayed on a pair of miniature color CRTs or LCDs. The appropriate perspective is calculated by the host, and views change as the "Cybernaut" looks up and down and turns from side to side.

Hand controls allow the traveler to move through an environment and grasp objects anywhere in the field of view or to jump to another region of the CAD universe along any axis.

NASA's Virtual Environment Interface Workstation lets engineers explore computer-generated realities.

If all goes well, Autodesk will be offering its corporate customers CyberSpace hardware and software options sometime next year. Final costs are hoped to be under $1,000 for goggles, gloves and host interface. And company engineers are even beginning work on a "visual programming language," says project manager William Bricken. It will partly comprise specific commands to help move through CyberSpace. "Submerge," for instance, might let a wearer pass through the floor to access a lower level of a simulation. Initially, such directives will likely be tied to hand movements (submerge could be indicated, say, by giving the thumbs down sign). Later, speech recognition could be added.

The complexity of the hand-sensing unit (dubbed DataGlove) has made volume pricing hard to peg down. For example, tests suggest that users who want to manipulate objects will also want some sort of tactile feedback. NASA has experimented successfully with miniature solenoid actuators that provide finger-pressure feedback proportional to the "force" the user is exerting.

Ames engineer Scott Fisher's Human Factors Research Division has championed the ways in which virtual realities can contribute to NASA's work in space, particularly in terms of the help that "telepresence systems" could lend to assembling and maintaining the space station.

Wearing stereoscopic goggles and sensor-laced gloves, telepresence workers on Earth might be able to see through a robot's eyes and manipulate objects with robotic hands located thousands and even millions of miles distant. Fisher has worked closely with engineers at VPL Research Inc. (Palo Alto, Calif.) to create a 15-sensor DataGlove that translates hand and finger movement into 8-bit data that is delivered to a custom interface.

VPL's Jaron Lanier is working as a consultant with AutoDesk. He's responsible for translating laboratory smart-glove sensor systems into large-scale commercial products. He was the catalyst behind the licensing of Mattel Toy's Power Glove con-

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NASA Views CyberSpace

No spacesuits are needed to explore computer-generated, or virtual, realities like CyberSpace. But these "total immersion" computer-graphics simulations hold the promise of new vistas and unprecedented navigational challenges.

NASA's premier system is called View (Virtual Environment Interface Workstation). It receives positioning data from a sensor-studded DataGlove and feeds the appropriate stereoscopic images into a wide-angle display system contained within a pair of stereoscopic goggles. NASA uses twin 640 × 220-pixel backlit LCDs to show computer-generated NTSC color graphics. Wide-angle optics ensure that the wearer's field of vision is fully filled by the display, and the graphics exhibit complete depth of field. When the CyberSpace explorer turns his head, the host makes certain the display is tracked accordingly.

Most objects are shown as wire-frame or color-shaded geometric images.

Travelers in this universe are not bound by the laws of physics but can rise and sink through "ceilings" and "floors" by pointing with the glove. Gravity can be lessened to the point at which a dropped light bulb will bounce several times without breaking. And travelers can travel through space at near the speed of computer signals.

The textural quality of the images and the speed with which they can be updated is all a matter of available computer horsepower. As power increases, researchers at NASA Ames Research Center, AutoDesk Inc. and VPL Research are certain that they'll come up with products that will extend the fledgling technology far beyond the laboratory—into industry, space and perhaps even the home.

—*By Richard Doherty*

HIGHER POWER TRANSISTORS TO PLAY IN X-BAND

InP extending solid state's range

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Apparently the presence of an RF signal has a stabilizing effect on the interface states. Power output for these devices drifted no more than 2 percent over a test period of 167 hours (about one week) of continuous operation.

Military systems that will benefit from the availability of higher-power X-band transistors will, for example, include missiles, radar, decoys and jammers. Extending the frequency range into a band will add satellite communications to the list.

In the past several years, the millimeter-wave frequency range from approximately 30 GHz to a few hundred GHz has received ever increasing attention. Solid-state devices and arrays operating at these frequencies will have applications in such areas as advanced missile systems, space and covert communications, radar, active tank defense, smart munitions and high-speed digital systems.

The first transistors to operate at millimeter-wave frequencies were GaAs-based field-effect transistors, the fastest of which are the high electron mobility transistors called HEMTs or MODFETs. Recently, however, similar structures based on InP have demonstrated approximately 50 percent higher-frequency operation. Cornell University has reported 1/10-micron-gate InGaAs/InP MODFET structures with a current gain cut-off frequency (f_t) of 170 GHz. What's more, General Electric has reported InAlAs/InGaAs/InP lattice matched ¼-micron HEMT devices demonstrating extrapolated maximum frequency of oscillation (fmax) of 380 GHz.

Similar structures using strained non-lattice-matched (pseudomorphic) channel layers and 1/10-micron gate lengths have been reported by Hughes Research Laboratories. The Hughes devices have demonstrated an f_t of 210 GHz and amplifier circuits employing these structures have exhibited noise figures of 0.8 dB with 9 dB gain at 60 GHz. Hughes also reports capacitively enhanced logic delays per stage of 6 ps at 24.5 mW per gate for ring oscillators using similar HEMT structures.

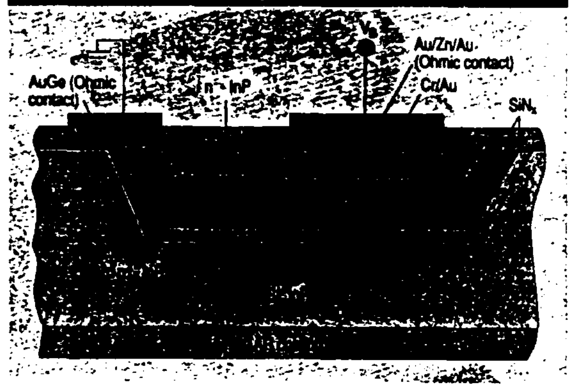
> **M**ilitary systems that will benefit from the availability of higher power X-band transistors will include missiles, radar, decoys and jammers.

In addition to field-effect transistors, InP-based heterostructure bipolar transistors (HBTs) offer—besides high speed—their own set of advantages including precise threshold control and compatibility with long-wavelength 1.3- to 1.55-micron optical devices for optoelectronic circuit integration. Researchers at AT&T Bell Laboratories have recently reported hot electron InP/InGaAs HBT devices demonstrating an f_t of 140 GHz. Ring oscillator results on these structures show a propagation delay per stage of 50 ps and a power consumption per stage of 4 mW.

InP-based high-speed optoelectronic ICs (OEICs) will soon greatly impact photonic systems ranging from fiber-optic telecommunications and signal processing to fiber-guided missiles. Photonic structures on InGaAs lattice-matched to InP substrates operate through the 1.55-micron wavelength attenuation minimum (−0.12 dB/km) of silica optical fibers. GaAs-based structures are limited to 0.85 micron radiation (2dB/km).

Thus, InP technology makes possible direct fiber-optic light transmission over distances more than an order of magnitude greater than can be achieved with GaAs-based devices. AT&T Bell Laboratories has reported an InGaAs PIN photodiode/InP junction field-effect transistor (JFET) OEIC receiver operating with a sensitivity of −33.9 dBm at a bit rate of 200 Mbits/s with a bit error rate of 10^9 at a wavelength of 1.55 microns. Meanwhile, researchers at Fujitsu have reported an InGaAs/InAlAs/InP OEIC receiver demonstrating a bit rate of 2 Gbits/s with −18.5-dBm sensitivity, with a bit error rate of 10^9 at 1.3 microns.

Planar p-i-n detector



InP-based devices and circuits are especially well-suited for space applications because of their high tolerance for the radiation experienced in the space environment. InP solar cells are already being tested in the radiation environment of space and, according to Irving Weinberg of NASA Lewis Research Center, one year's data available on InP solar cells tested on satellite Lips-3 has shown that there is no degradation in the performance of these devices.

Laboratory data indicates that for 10 years in orbit, InP solar cell efficiencies are expected to degrade by only 3 percent, while for GaAs the degradation should be approximately 16 percent and for Si cells about 25 percent. NASA Lewis has reported air-mass zero total area efficiencies of 18.8 percent in n/p homojunction solar cells fabricated for them by Spire Corp. using OMCVD and ion implantation techniques. Theoretical modeling predicts efficiencies of 21 percent can be achieved on InP cells.

High-speed spatial light modulators (SLMs) could increase the performance of many military signal-handling systems. One approach to SLM devices is the use of the quantum-confined stark effect in multi-quantum-well (MQW) layers with charge-coupled devices (CCDs) used to spatially program the electric field across an array, thereby providing control of the transmitted light intensity.

Colorado State University is engaged in the development of SLM devices fabricated on InP/InGaAs structures grown by GSMBE. Insulated-gate InP CCDs fabricated at NOSC have demonstrated a clock rate of 800 MHz. These used a two-level overlapping gate structure analogous to Si CCDs. This is not feasible on GaAs because of the lack of a compatible insulator.

Spire Corp. (Bedford, Mass.) is progressing well with growing high-quality InP by OMCVD on GaAs and GaAs-coated Si wafers. And, this could cut the cost of some InP devices and circuits through the use of less expensive substrates. In addition, this capability opens up the possibility of integrating on a single chip InP-based high-speed, high-power and optoelectronic devices with GaAs and Si electronics.

For more complete information of the latest innovations in InP-based devices and circuits, see the "Proceedings of the First International Conference on InP and Related Materials for Advanced Electronic and Optical Devices," held in Norman, Okla., March 20 to 22, 1989, and due out in August 1989 from SPIE. The "Proceedings of the First InP Microwave/Millimeter-Wave Technology Workshop," held in San Diego, Jan. 25 to 26, 1989, is also to be published by NOSC around September 1989 and will be available through the Defense Technical Information center (DTIC) in Alexandria, Va.